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Prospects of biodiesel from Pongamia in India

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A B S T R A C T

Pongamia is forest-based tree containing non-edible oil and has a large production potential of biodiesel which can grow on any type of soil, needs minimum input and management, have low moisture demand, productive life is more than 40 years and seeds have 28–34% oil content. Biodiesel yield of 99% is obtained from Pongamia oil by transesterification under the molar ratio of 6:1 of alcohol to oil with Sodium hydroxide as a catalyst of 0.5 vol% and operating temperature of 60 °C with time for production process being 1 h. The study shows that brake specific fuel consumption and brake thermal efficiency of B_{20} biodiesel from Pongamia is quite comparable to diesel. The hydrocarbon and carbon monoxide gas emissions are quite low in case of Pongamia biodiesel as compared to diesel. This paper describes the various aspects of Pongamia as potential fuel in India.

Contents

1. Introduction

The rising price of petroleum fuel, depletion of oil reserve and environmental problems related to fossil fuels are the main driving force that lead to the search for the alternative source of energy. In this scenario, the prospect of biodiesel is very promising as an environment-friendly and sustainable energy source [1]. The development of biodiesel as an alternative and renewable source of energy for the mechanized agricultural and transportation sector has become critical in the national effort towards maximum self-reliance for the corner stone of our energy security strategy [2]. The main feedstock for biodiesel production in India is non-edible oils obtained from plant species such as *Jatropha* (*Jatropha curcas*), *Pongamia* (*Pongamia pinnata*) and *Polanga* (*Calophyllum inophyllum*) due to the high cost of edible oils. The natural distribution of *Pongamia* is along coasts and river banks in India and Myanmar and also in humid tropical lowlands in the Philippines, Malaysia, Australia, the Seychelles, the United States of America and Indonesia. *Pongamia pinnata* also called as Derris indica is a monotypic genus belonging to the Leguminaceae family and have multipurpose benefits [1,3].

Table 1 shows the forest area of *Jatropha* and *Pongamia* tree in various states of India. The physico-chemical properties and availability of the oil vary considerably with location, and also

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Table 1
Area (ha) of Major tree for biodiesel production in India [4].

Name of State	Jatropha	Karanja
Andhra Pradesh	1500	7009
Assam	100	712
Arunchal Pradesh	235	28
Bihar	200	180
Chattisgarh	304,152	1895
Dadar nagar haveli	45	53
Gujarat	1300	718
Delhi	–	168
Harayana	1405	553
Himachal Pradesh	489	843
Jammu and Kasmir	9	5
Jharkhand	800	1416
Karnataka	670	3580
Kerla	50	685
Madhya Pradesh	374,648	4235
Maharashtra	2360	2201
Manipur	450	19
Meghalaya	446	347
Mizoram	380	–
Nagaland	490	–
Orissa	–	1506
Puduchery	–	1830
Punjab	300	319
Rajasthan	10,554	595
Sikkim	150	–
Tamilnadu	900	4176
Tripura	150	393
Uttarpradesh	12,000	1929
Uttarakhand	13,500	513
West Bengal	21,500	481
Total	**748,782**	**36,000**

according to climate and seasons. *Pongamia* oil available in large quantity is a good feedstock for biodiesel synthesis with production of 200 million tonnes of oil per year in India [5]. The seed contains an average of 28–34% of oil with high percentage of polyunsaturated fatty acids. The plant gives seeds after 3rd year of plantation and then in 4th year it does not give any seeds and then in 5th year it again gives seeds. Historically, *Pongamia* has been used as folk medicinal plant, particularly in Ayurvedha and Siddha systems of Indian medicine. All parts of the plant have been used as a crude drug for the treatment of tumours, piles, skin diseases, itches, abscess, painful rheumatic joints wounds, ulcers, diarrhea etc. Besides, its press cake can be used as fodder but should not be fed to animals alone since it contains a number of toxins including karanjin. It has also been recognized to possess applications in agriculture and environmental management, with insecticidal and nematicidal activities and production of fish poison. The tree is important for shade, ornamental value, seed oil, and plant fodder. After oil extraction the residue of *Pongamia* seed can be used as green manure as it is rich in protein and nitrogen. The leaves, roots and flowers are reported to possess medicinal properties. This leguminous tree contains greater food reserves and around 800–1200 seeds are found to weigh 1 kg [1].

2. Pongamia oil in India

In Indian context, the use of edible oils for engine fuel is not feasible; however, there are several non-edible oilseed species such as *Pongamia* (*Pongamia pinnata*), *Jatropha* (*Jatropha curcas*), *Neem* (*Azadirachta indica*), *Mahua* (*Madhuca indica*), *Simarouba* (*Simarouba indica*) etc., which could be utilized as a source for production of oil. Among these, *Pongamia* is an oil seed bearing tree, which is non-edible with only 6% being utilized out of 200 million tonnes production per annum [6,7]. *Pongamia* is a native to humid and subtropical environments having annual rainfall ranging from 500 to 2500 mm in its natural habitat. The maximum temperature ranges from 27 to 38 °C and the minimum 1–16 °C. It can grow on most soil types ranging from stony to sandy to clay, including verticals. It does not do well in dry sands. It is highly tolerant to salinity. It can be propagated either by seeds or by root suckers. The yield of kernels per tree is between 8 and 24 kg. The average diameter of kernel was calculated by using the arithmetic mean and geometric mean of the three axial dimensions. The arithmetic mean diameter, Da of the kernel is calculated by using

Da = (length + width + thickness)/3 [8]

In India the plant is distributed in Andhra Pradesh, Orissa, Bihar, Jharkhand, Chhattisgarh, Madhya Pradesh, Karnataka, Kerala, West Bengal and Maharashtra. Table 2 provides the various local names of *Pongamia* in various states of India.

Table 2
Local Name of Pongamia in Various States of India [9]

S. no	State	Local name of Pongamia
1	Andhara Pradesh	Gaanug,Pungu
2	Karnataka	Honge,Huligili,Batti,Uggemara
3	Tamilnadu	Pongam,Ponga,Kanga
4	Kerla	Punnu,Minnari
5	West Bengal	Dalkarancha
6	Orissa	Koronjo,Konga
7	Madhya Pradesh	Karanja,Karanj
8	Uttar Pradesh	Karanja,Sukhchain,Karanj,Papri
9	Haryana	Sukhchain,Karanj,Papri
10	Maharashtra	
11	Gujarat	
12	Rajasthan	
13	Punjab	
14	Assam	Poonga

3. Properties of Pongamia oil

Pongamia is medium sized fast-growing ever green tree of 12–15 m height, branches spread into hemispherical crown of dense green leaves. It has a disagreeable odour and bitter taste. Pods are elliptical, 3–6 cm long and 2–3 cm wide thick walled and usually contains single seed. Seeds are 10–20 mm long and light brown in colour. *Pongamia* can survive in adverse conditions like draught, heat, frost, salinity, etc. The freshly extracted *Pongamia* oil is yellowish orange to brown and rapidly darkens on storage. The oil is extracted from the kernel by traditional expeller. The oil contains toxic flavonoids such as karanjin and di-ketone pongamol as major lipid associates, which make the oil non-edible. The oil has been used as raw material for leather tanning, lighting and to a smaller extent in soap making, medicine and lubricants [6,10]. Air-dried *Pongamia* kernels have typically 19.0% moisture, 27.5% fatty oil, 17.4% protein, 6.6% starch, 7.3% crude fiber, and 2.4% ash [11].

Table 3 provides the fatty acid composition of *Pongamia* oil. *Pongamia* oil is widely used for biodiesel production because it has the potential to provide an environmentally acceptable, alternative to conventional diesel engine fuels [20,21].

Table 4 shows various fuel properties of *Pongamia* oil. The high flash point and high calorific value of *Pongamia* oil make it suitable fuel but due to its high viscosity it cannot be used directly in engine; therefore it has to be converted into biodiesel by the process of transesterification.

4. Production of Pongamia biodiesel

Biodiesel is produced from refined/edible oils using methanol and alkaline catalyst. However, wide range of non-edible oils are

Table 3
Fatty Acid Composition Of Pongamia Oil [1,7,10–19].

Fatty acid	Structure	% Fatty acid
Palmitic acid	(C16:0)	3.7–14.1
Strearic acid	(C18:0)	2.4–10.9
Oleic acid	(C18:1)	44.5–71.3
Linoleic acid	(C18:2)	10.8–27.1
Linolenic acid	(C18:3)	3.6–6.3
Capric Acid	(C10:0)	0.1
Lauric acid	(C12:0)	0.1
Arachidic Acid	(C20:0)	0.8–4.7
Behenic Acid	(C22:0)	0.1–5.3
Total satuarted acid		**20.5**
Total unsaturated acid		**79.5**

Table 4
Fuel properties of Pongamia Oil [2,5,7,9,13,15,17, 22–25].

Fuel properties	Pongamia oil
Specific gravity (kg/L)	0.912–0.940
Kinematic viscosity (mm^2/s) at 40 °C	27.84–38.2
Flash point (°C)	205–270
Calorific value (MJ/Kg)	34–38.5
Acid value (mgKOH/gm)	3.8–5.06
Free fatty acid	2.53–20
Sponification value	185–195

available, the alkaline transesterification of these oils is difficult due the presence of large amount of free fatty acids (FFA). Hence these free fatty acids form soap with alkali, it is mandatory to reduce FFA present in non-edible oils. Acidic ion exchange resins can be used to decrease FFA level. There are four ways in which oils and fats can be converted into biodiesel namely transesterification, blending, micro-emulsion and pyrolysis. The most common method to produce biodiesel is transesterification of vegetable oils and animal fats in the presence of a catalyst such as acid, alkali or enzyme. In this reaction, vegetable oils or animal fats and alcohol react in the presence of potassium hydroxide used as catalyst. Methanol is generally used as a solvent for this purpose due to the low cost, smaller chain length and easier separation of biodiesel as compared with higher alcohol [2,26,27]. The transesterification is first done by E. Duffy and J. Partrick in year 1853 [28]. The first transesterified vegetable oil was used in heavy duty vehicle in South Africa before world war-II. The name biodiesel has been given to transesterified vegetable oil to describe its use as a diesel fuel. Transesterification reduces the viscosity of vegetable oils without affecting the calorific value of the original fuel. Therefore, fuel atomization, combustion and exhaust emissions display better results after transesterification [29]. The production of biodiesel from non-edible oil is challenging due to the presence of undesirable components especially free fatty acids (FFA) and water [14,30]. Biodiesel is an alternative diesel, made from renewable biological sources such as vegetable oils and animal fats by chemically reacting oil or fat with an alcohol, in the presence of a homogeneous and heterogeneous catalyst. The products of the reaction are mixture of methyl esters, which are known as biodiesel, and glycerol [31].

4.1. Homogeneous catalysis

Transesterification is a reversible reaction and proceeds essentially by mixing the reactants in which the catalysts is a liquid acid or a liquid base [31] .

4.2. Heterogeneous catalysis

It is not possible to perform a basic transesterification process for high free fatty acid (FFA) content oil and decrease the conversion of oil to methyl ester due to saponification reaction. The use of solid catalyst is recommended for high free fatty acid containing oil. This is because the solid acid catalysts can simultaneously catalyse the transesterification of triglycerides and esterification of free fatty acid (FFA) present in oil to methyl esters. Solid acid catalysts have the strong potential to replace homogeneous catalysts, eliminating separation, corrosion and environmental problems [31]. The reaction parameters such as catalyst concentration, alcohol/oil molar ratio, temperature, and rate of mixing were optimized for production of *Pongamia* oil methyl ester (POME). The yield of methyl esters from *Pongamia* oil under the optimal condition was 97–98% [6]. Biodiesel production from high free fatty acid oil needs a two-step transesterification process, i.e., acid esterification followed by alkali transesterification to get high biodiesel yield. In acid esterification, 25 mL of oil was poured into the flask and heated to about 45 °C, then 8 mL of methanol was added and stirred at low stirring speed for 10 min followed by 0.5% (v/ v) of acid. The treated oil having acid value less than 2 ± 0.25 mg KOH/g was used for the alkali transesterification reaction. It has been reported that transesterification would not occur if FFA content in the oil was above 3%. The experimental set-up for alkali catalysed transesterification was the same as that used for acid catalysed pretreatment. According to this process 0.45 g of KOH was dissolved in 10 mL of methanol and half of that was poured into the flask containing an unheated mixture from acid esterification step and stirred for 10 min. After 10 min, the mixture was heated and stirred continuously to about 60 °C, and then the remaining methoxide was added to it and the reaction continued for 2 h [32]. The free fatty acid of crude *Pongamia* oil was reduced and biodiesel was synthesized from pretreated oil under microwave irradiation. The process variables such as irradiation time, methanol–oil ratio and KOH concentration for pretreatment step; irradiation time, methanol–oil ratio and KOH concentration were optimized through the Box–Behnken experimental design. The free fatty acid of crude *Pongamia* oil was reduced to $1.11 \pm 0.07\%$ with an optimal combination of 190 s irradiation time (180 W), 33.83 (w/w) % methanol–oil ratio and 3.73 (w/w) % acid concentration. An optimal combination of 150 s irradiation time, 33.4 (w/w) % methanol–oil ratio and 1.33 (w/w) % KOH concentration yielded $89.9 \pm 0.3\%$ biodiesel [5]. The *Pongamia oil* has high free fatty acid (FFA) and necessitates a pretreatment step to reduce FFA. The FFA needs to be reduced below 1% in order to obtain high biodiesel yield through alkali catalysed transesterification. Free fatty acid of crude oil is generally reduced through an acid catalysed esterification reaction under conventional heating. In conventional method of biodiesel synthesis the reaction time and temperature are 30 min to 2 and 55–65 °C respectively. Theoretical methanol–oil molar ratio is 3:1, but a higher molar ratio is used in order to shift the equilibrium reaction towards completion and the optimal methanol–oil molar varies from 6:1–9:1. Here KOH is preferred as the homogeneous catalyst for transesterification of triglycerides and it depends upon the % FFA present in the oil. In order to reduce % of FFA in oil, oil is pretreated through esterification reaction. Intensity of mixing has negligible effect beyond 300 rpm [3]. Kamath et al. [5] performed the conversion of crude *Pongamia* oil with high FFA (8.8%) was reduced to 1.1% by pretreating the oil with methanol (33.83 w/w% methanol–oil ratio) using H_2SO_4 as a catalyst (3.73 w/w%) and irradiating for 190 s at 180 W. It is reported that the transesterification of triglycerides by methanol has proved to be the most promising process as shown in Fig. 1.

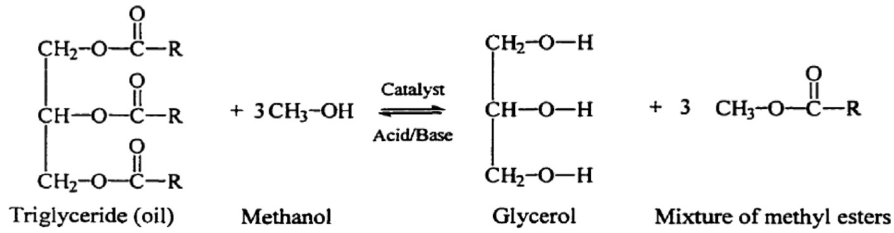


Fig. 1. Transesterification reaction.

Table 5
Various parameter for Pongamia biodiesel production.

Oil	Catalyst and its concentration (w/w)	Molar Ratio (alochol:oil) (v/v)	Reaction temperature (°C)	Mixing intensity (rpm)/time (h)	% Yield	Reference
Pongamia	KOH (0.25–1.5%)	6:1	65	600 rpm	–	[6]
Pongamia	KOH (1%)	–		3 h	96	[6]
Pongamia	–	6:1		3 h	97	[6]
Pongamia	–	24:1		0.5 h	97	[6]
Pongamia	KOH (1%)	6:1	37	600 rpm	85	[6]
Pongamia	KOH (1%)	6:1	50	600 rpm	96	[6]
Pongamia	KOH (1%)	6:1	65	600 rpm	97	[32]
Pongamia	Step-I H_2SO_4 (1%)	6:1	50	–	80	[32]
	Step-II KOH (0.5%)	9:1	50	–		
Pongamia	KOH	10:1	60	–	92	[10]
Pongamia	–	6:1	65	–	89	[26]
Pongamia	Step-I KOH	3:1	45	–	80	[12]
			60	–	83	
	Step-II NaOH	10:1	45	–	83	
			60	–	92	
Pongamia	NaOH (0.5%)	6:1	60	1 h	99	[12]
			32	4 h	99	
Pongamia	KOH (1%)	10:1	60	–	92	[12]
Pongamia	–	11.5:1	–	2 h	91	[2]
Pongamia	KOH (1%)	6:1	60	1 h/250 rpm	–	[14]
Pongamia	–	–	60	1.5 h	95	[14]
Pongamia	Li/Cao (2%)	12:1	65	8 h	94.9	[33]
Pongamia	Step-I H_2SO_4 (1%)	6:1	65	4 h	89.8	[34]
	Step-II H_3PO_4 (2%)	6:1	65	4 h	15	
Pongamia	Step-I KOH (1%)	6:1	65	1 h	–	[7]
	Step-II KOH (1%)	6:1	78	1.5 h	–	
Pongamia	Sulfated Zirconia (1%)	9:1	60	2 h	–	[15]
Pongamia	KOH (1%)	6:1	65	3 h	89	[35]
Pongamia	KOH (1%)	3:1	45	1.5 h	92	[35]
Pongamia	KOH (1%)	10:1	60	1.5 h	95	[35]
Pongamia	KOH (1%)	27:1	60	–	–	[35]
Pongamia	H_2SO_4 (0.25–2%)	3:1	50	0.75 h	94	[35]
Pongamia	KOH (0.3–1%)	3:1	50	0.5 h	80	[35]
Pongamia	H_2SO_4 (0.5%)	6:1	65	–	91	[35]
Pongamia	KOH (1%)	6:1	65	–	97	[35]
Pongamia	H_2SO_4 (1%)	6:1	60	–	95	[35]
Pongamia	KOH (1%)	6:1	60	1 h	97	[35]
Pongamia	LiCao (1–3%)	3:1	35-85	2 h	99	[35]
Pongamia	ZnO (0.1%)	10:1	120	24 h	83	[35]
Pongamia	KOH (1%)	6:1	65	2 h/360 rpm	98	[16]
Pongamia	KOH	10:1	60	–	92	[16]
Pongamia	ZnO	10:1	105	1.5 h	94.8	[16]
Pongamia	LiCaO (2%)	12:1	65	8 h	90	[16]
Pongamia	KOH (1%)	6:1	60	–	88.6	[16]
Pongamia	KOH (0.68%)	6:1	70	24 h	92	[16]
Pongamia	NaOH (0.68%)	12:1	–	–	85	[29]
Pongamia	KOH (0.68%)	12:1	–	–	82	[29]
Pongamia	NaOH (0.68%)	10:1	–	–	85	[29]
Pongamia	KOH (0.68%)	10:1	–	–	82.5	[29]
Pongamia	NaOH (0.68%)	8:1	–	–	89.5	[29]
Pongamia	KOH (0.68%)	8:1	–	–	89.5	[29]

Also molar ratio of alcohol to vegetable oil and reaction temperature, catalyst, pressure, reaction time and the contents of the free fatty acids and water in oils are the variables affecting the methyl ester yield during the transesterification reaction. It is also reported that in the supercritical methanol transesterification method, the yield of conversion raises up to 96% in 10 min [10].

Table 5 shows that various conditions of biodiesel production from *Pongamia* oil which shows that max yield of 99% is achievable

by putting the oil in certain specific conditions of time, temperature, molar ratio and catalyst nature and its concentration. Naik et al. [33] performed the transesterification of *Pongamia* oil with methanol using solid basic catalysts. Alkali metal-impregnated calcium oxide catalysts, due to their strong basicity and it catalyse the transesterification of triacylglycerols. The alkali metal (Li, Na, K) doped calcium oxide catalysts were prepared and used for the transesterification of *Pongamia* oil containing 0.48–5.75% of free fatty acids (FFA). The reaction conditions, such as catalyst concentration, reaction temperature and molar ratio of methanol/oil, were optimized with the solid basic Li/CaO catalyst. This catalyst, at a concentration of 2 wt%, resulted in 94.9 wt% of methyl esters in 8 h at a reaction temperature of 65.7 °C and a 12:1 M ratio of methanol to oil, during methanolysis of *Pongamia* oil having 1.45% FFA. The yield of methyl esters decreased from 94.9 to 90.3 wt% when the FFA content of Pongamia oil was increased from 0.48% to 5.75%.

Khayoon et al. [34] reported that methyl esters were synthesized from crude *Pongamia* oil (PO) by single step esterification with methanol using acid (H_2SO_4) and phosphoric acid (H_3PO_4) as catalysts in a homogeneous batch process. H_3PO_4 was less active than H_2SO_4 during the process as it presented very low ester yields (< 20%) for the various molar ratios of fatty acid to alcohol studied. With H_2SO_4 as catalyst, the yield was as high as 89.8% at 65 °C after 5 h. Baiju et al. [7] state that biodiesel is developed from both through the methyl as well as ethyl alcohol route (methyl and ethyl ester) from *Pongamia* oil as an alternative diesel fuel. The major problem of using neat *Pongamia* oil as a fuel in a compression ignition engine arises due to its very high viscosity. Transesterification with alcohols reduces the viscosity of the oil and other properties have been evaluated to be comparable with those of diesel. The physical and chemical properties of ethyl esters were comparable with that of methyl esters. However, viscosity of ethyl esters was slightly higher than that of methyl esters. Cold flow properties of ethyl esters were better than those of methyl esters. Performance and exhaust emission characteristics of the engine were determined using petro diesel as the baseline fuel and several blends of diesel and biodiesel as test fuels. Results show that methyl esters produced slightly higher power than ethyl esters.

Thiruvengadaravi et al. [15] produced biodiesel by acid-catalysed esterification of high free fatty acid (FFA) *Pongamia* oil (PO). Pretreated PO was converted to biodiesel by a process of alkaline catalysed transesterification. Optimum acid-catalysed esterification was achieved using 1% Sulfated Zirconia (SZ) as a solid acid catalyst with a methanol-to-oil ratio of 9:1, temperature at 60 °C and reaction time of 2 h. During this process, FFA were converted into fatty acid methyl esters. The acid value of Pongamia oil was reduced to 1.3 mg KOH/g from 12.27 mg KOH/g, which confirms the conversion. There are two ways in which oils and fats can be converted into biodiesel: transesterification and pyrolysis, between them transesterification being the most common. Conversion is complicated if the oil contains large amounts of FFA (> 2% w/w) which form soap with the alkaline catalyst. The soap can prevent separation of the biodiesel from the glycerine fraction. Work with feed stocks having higher FFA levels using alternative processes have been carried out. A two-step pretreatment to reduce the FFA of yellow grease and brown grease to less than 1%, down from 12% and 33%, respectively, completing the transesterification reaction with an alkali to produce biodiesel. A two-step process for biodiesel production is found to have been effective with respect to oils with high FFA content [18]. Simultaneous esterification and tranesterification in a single step, with a base catalyst is not possible due to soap formation and with an acid catalyst, it takes much longer time to complete. Musthafa et al. [22] prepared the *Pongamia* biodiesel by the single step base catalysed transesterification method. Bankovic et al. [35] used methanol and rarely ethanol for biodiesel production because the methanolysis is faster than ethanolysis and FAME yields are higher than those of FAEE yields. The advantage of better oil solubility in ethanol than in methanol was used such that the ester yield did not increase when the alcohol:oil molar ratio increased above the molar ratio of 16:1. Blending conventional diesel fuel with esters (usually methyl esters) of vegetable oils is presently the most common form of biodiesel [36].

5. Pongamia biodiesel

Biodiesel has been categorized as a “green fuel”, being the most attractive substitute to the conventional petro-diesel. It is a non-petroleum based fuel that composes of fatty acid alkyl esters synthesized through the transesterification and/or esterification reactions of triglycerides (TGs) of fatty acids (C_{12}–C_{22}) with short chain alky source (methanol, ethanol, propanol or recently dimethyl carbonate). The term “FAME” that refers to fatty acid methyl esters, is commonly used to describe the biodiesel produced by methanol. Biodiesel combustion is environment friendly, offers good storage properties, bio renewable in nature, has a higher flash point and cetane number than petro-diesel, non-aromatic and completely biodegradable (capable of being broken down into harmless products) [37].

Table 6 shows the various fuel properties of Pongamia biodiesel and its lend. It can be observed that the properties of B_{20} fuel are quite comparable to diesel. In near future it can replace diesel. The calorific values of all the biodiesel and their blends are lower than that of diesel because of their oxygen content. The presence of oxygen in the biodiesel helps for complete combustion of fuel in the engine. The flash point of all the biodiesel and their blends is lowered by transesterification but it is still higher than that of diesel. Addition of a small quantity of biodiesel with diesel

Table 6
Fuel properties of Pongamia Biodiesel and its blends [2,7,10,15,17,22,23,26,27,32,35,36,38,39].

Fuel properties	B-100	B-80	B-60	B-40	B-20	Diesel
Specific gravity	0.876–0.939	0.869	0.864	0.856	0.848	0.80
Kinematic viscosity(mm^2/s) at 40 °C	3.99–11.82	2.60–5.01	3.81–5.42	3.51–4.63	3.01–3.49	1.3–4.1
Flash point (°C)	147–196	52–149	84–123	81–99	76–96	60–80
Calorific value (MJ/Kg)	35.56–42.17	42.21–42.31	37.35–42.93	37.85–43.15	38.28–43.6	44.8
Cloud point (°C)	−3 to 22.5	12.3–21	11.6–20.6	10.9–18	7.1–14.1	−15 to 5
Pour point (°C)	−4 to 15	4.9–13	4.3–9.4	3.6–5.7	1.8–3.6	−35 to −15
Density	869–884	871	859	854	851–862	830
Cetane number	47.78–57.9	–	–	–	51	40–55
Oxidation stability at 110 °C, h	2.3–11.6	–	–	–	–	–
Acid Value (mgKOH/gm)	0.62–0.80					–

increases the flash point of diesel [2]. Biodiesel is a non-toxic, biodegradable, renewable fuel that can be produced from a range of organic feedstock including fresh or waste vegetable oils, animal fats, and oilseed plants. Biodiesel has significantly lower emissions than petroleum-based diesel when it is burned, whether used in its pure form or blended with petroleum diesel. It does not contribute to a net rise in the level of carbon dioxide in the atmosphere and leads to minimize the intensity of greenhouse effect [32]. For the biodiesel to be marketable it needs to conform with standard fuel specifications such as ASTM, which restricts acid value of biodiesel to 0.5 mg KOH/g [5]. Bio fuels are renewable, can supplement fossil fuels, reduce GHGs and mitigate their adverse effects on the climate resulting from global warming and carbon neutral [2,10].

5.1. Oxidation stability of Pongamia biodiesel

Vegetable oils and their esters (biodiesel) undergo oxidation and degenerate more quickly than mineral diesel. The unsaturated fatty acids present in vegetable oils are susceptible to oxidation. One of the main criteria used for the quality assessment of biodiesel is storage oxidation stability [30]. Oxidation of the esters during the long-term storage can lead to problems in the utilization of biodiesel in the engine and can lead to rough engine operation [40]. One of the major drawbacks of biodiesel over mineral diesel is that it can be more susceptible to oxidation at room temperature. It is due to the chemical structure of fatty acid methyl esters. Saturated fatty acid methyl esters ($C_{14:0}$, $C_{16:0}$ and $C_{18:0}$) increases cloud point, cetane number and improves stability; however poly-unsaturated esters ($C_{18:2}$ and $C_{18:3}$) decreases same. Fuel thickening, formation of gums and sediments which lead to filter clogging and injector fouling occur due to poor oxidation stability (OS) of fuel. The fatty acid methyl esters undergo a chemical process called autoxidation when biodiesel is stored for long time and exposed to air. Autoxidation converts R–H group to R–O–O–H (hydroperoxide) group in contact with molecular oxygen, which again degrade and rearrange to carboxylic acids and carbonyls through chain oxidation reactions. The study investigates the impact of various synthetic phenolic antioxidants on the oxidation stability and storage stability of *Pongamia* biodiesel (PBD). Engine and injection pump producers insisted on the parameter of oxidation stability which was finally fixed at a minimum limit of a 6-h induction period at 110 °C. The method adopted for determination of the oxidation stability is the so called Rancimat method which is commonly used in the vegetable oil sector [41].

The results of Rancimat experiments show that the induction point (IP) increased substantially on adding certain antioxidants to the *Pongamia* biodiesel (Fig. 2, Table 7).

The above table shows that pyrogallol (PY) is the best antioxidant to show the best improvement in the oxidative stability of PBD, the induction time being enhanced to 34.35 h at a PY concentration of 3000 ppm at 110 °C .

5.2. Cold flow property of Pongamia biodiesel

The low temperature flow properties of biodiesel are characterized by cloud point (CP) and pour point (PP) and these must be considered when operating compression–ignition engines in moderate temperature climate during winter months. Cloud point (CP) is the temperature at which a sample of the fuel starts to appear cloudy, indicating that wax crystals have begun to form which can clog fuel lines and filters in a vehicle's fuel system and where as Pour Point (PP) is the temperature below which the fuel will not flow. High CP and PP values of biodiesel can be explained by high contents of the saturated fatty acid alkyl esters because the unsaturated fatty acid alkyl esters have lower melting points than the saturated fatty acid alkyl esters [42]. Sarin et al. [42] correlate the amount of unsaturated fatty acid with cold flow properties as follows:

$$CP = -0.576 \times X + 48.255$$

$$PP = -0.626 \times X + 45.594$$

where X is % unsaturated fatty acid [42]. Pour points of *Jatropha* and *Pongamia* methyl ester were found to vary between −6 to 2 °C and −3 to −1 °C [32].

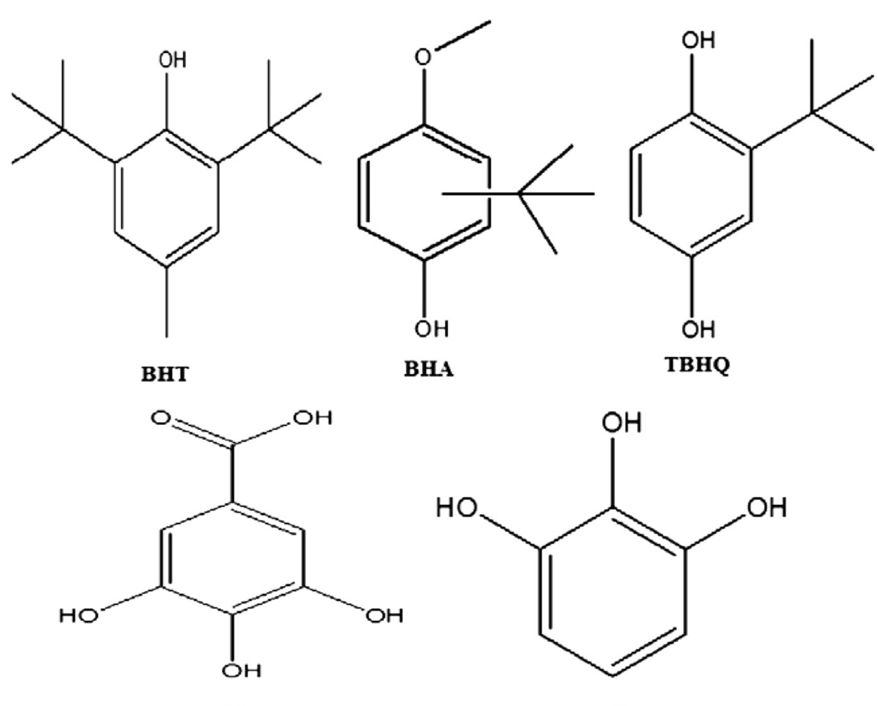


Fig. 2. Chemical structures of various phenolic antioxidants. [41].

Table 7
Induction Time of Pongamia Biodiesel with different antioxidant at different concentrations [41]

S. no	Antioxidant	Induction time (without antioxidant) (h)	Induction time (h)			
			500 ppm	1000 ppm	2000 ppm	3000 ppm
1	BHT	0.33	0.80	1.76	3.14	4.88
2	BHA	0.33	0.76	1.70	2.96	5.02
3	TBHQ	0.33	0.86	1.56	2.91	6.19
4	GA	0.33	0.67	0.76	0.82	0.88
5	PY	0.33	2.86	4.99	25.02	34.35

6. Impact of Pongamia biodiesel on engine performance

Engine tests have been conducted to get the comparative measures of brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and emissions such as CO, CO_2, HC, NO_x to evaluate the behaviour of Pongamia Biodiesel and diesel in varying proportions. The results reveal that blends of Pongamia Biodiesel with diesel up to 40% by volume (B_{40}) provide better engine performance (BSFC and BSEC) and improved emission characteristics [10]. The blends of Pongamia biodiesel (B_{40}) could replace the diesel for engine applications for getting less emissions and better performance and will thus help in achieving energy economy, environmental protection and rural economic development.

The table 8 shows that engine performance is increased by the use of Pongamia biodiesel and its blends; the emission levels are also lower in case of Pongamia biodiesel as compared to diesel. The emissions in the exhaust gas compared to petro-diesel i.e. carbon monoxide (CO) by 46.7%, unburned hydrocarbons (UHC) by 45.2% and particulate matter (PM) by 66.7% while, NO_x emissions have been reported to increase due to the high oxygen content of biodiesel [37]. Chauhan et al. [38] compared the performance, emissions and combustion characteristics of biodiesel derived from non-edible Pongamia oil in an unmodified diesel engine and to compare the results with the baseline results of diesel fuel. Important physicochemical properties of Pongamia oil after transesterification were experimentally evaluated and found within acceptable limits of relevant standards. The performance parameters evaluated are brake thermal efficiency of Pongamia biodiesel with different compositions at 5%, 10%, 20%, 30% and 100% with mineral Diesel. BTE was about 3–5% lower with Pongamia biodiesel and its blends with respect to diesel. Also, emission parameters such as carbon monoxide, carbon dioxide, UBHC (unburned hydrocarbon), oxides of nitrogen and smoke emission for different test fuels were also measured. Unburnt hydrocarbon, CO, CO_2 and smoke were lower with Pongamia biodiesel fuel. However, NO_x emissions of *Pongamia* biodiesel and its blend were higher than that of diesel. The combustion analysis was done using peak cylinder pressure and heat release rate with respect to crank angle. The peak cylinder pressure and heat release rate was lower for *Pongamia* biodiesel. Jaichandar and Annamalai [23] investigated the blend of 20% *Pongamia* Oil Methyl Ester (POME) with standard diesel as fuel and with three types of combustion chambers namely Hemispherical combustion chamber, Toroidal combustion chamber and Shallow depth combustion chamber without altering the compression ratio of the engine. The test results showed that brake thermal efficiency for toroidal combustion chamber is higher than that of the other two types of combustion chambers. Pandian et al. [43] investigated the effect of injection system parameters such as injection pressure, injection timing and nozzle tip protrusion on the performance and emission characteristics of a twin cylinder water cooled naturally aspirated CIDI engine. Bio-diesel scores very well as an alternate fuel of choice as it helps in decreasing dependence on fossil – fuels and also as it has almost no sulphur. Higher cetane of biodiesel as compared to petro diesel implies its much improved combustion profile in an internal combustion engine. The pollutant components from exhaust are also decreased by using biodiesel [44]. The results from the experiments suggest that biodiesel from non-edible oil like Pongamia and its blends with diesel could be a potential fuel for diesel engine and will play a vital role in the near future Table 8.

7. Main finding

The literature shows that:

1. Pongamia Pinnata as fuel source is in very nascent stage in India. Out of 200 million tonnes only 6% is used for fuel production
2. Biodiesel yield of 99% is obtained from Pongamia oil by transesterification under the molar ratio of 6:1 of alcohol to oil with Sodium hydroxide as a catalyst of 0.5 vol% and operating temperature of 60 °C with time for production process is 1 h.
3. Pyrogallol is best antioxidant for Pongamia biodiesel to improve oxidation stability.
4. BSFC and BTE of B20 Pongamia Biodiesel are comparable to diesel.
5. CO, HC and Particulate emission are lower in case of Pongamia biodiesel as compare to diesel.
6. CO_2 and NO_x emission are higher in case of Pongamia biodiesel due to the high oxygen content of biodiesel.

8. Conclusion

The study shows that availability of Pongamia trees in various states of India is in abundance, but inspite of that use of Pongamia oil is in very nascent stage in India. Out of enormous production of 200 million tonnes, only 6% of oil is used as fuel. Biodiesel yield of 99% is obtained from Pongamia oil by transesterification under the molar ratio of 6:1 of alcohol to oil with sodium hydroxide as a catalyst of 0.5 vol% and operating temperature of 60 °C with time for production process is 1 h. The oxidation stability of Pongamia biodiesel is improved by using Pyrogallol as antioxidant. It is observed that various engine properties of B_{20} biodiesel such as brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and brake thermal efficiency (BTE) are similar to that of diesel and emissions of harmful gases such as CO and HC and particulate emission are lower as compared to diesel. The only disadvantage associated with the use of Pongamia biodiesel as fuel is emission of harmful CO_2 and NO_x gases due to presence of high oxygen content in biodiesel. In the coming future it is observed that Pongamia biodiesel will be developed as an alternative source of energy.

Table 8
Impact of Pongamia biodiesel on engine performance

S. no	Engine specification	Fuel	Results	References
1	**Diesel Engine:** Rated speed: 1500 rpm Brake power: 3.68 kW Stroke length: 110 mm Diameter of cylinder: 87.5 mm Compression ratio: 16.5:1	Pongamia Biodiesel (B20, B40, B60, B80, B100), Diesel	1 BSFC for B20 and B40 is equal or less to diesel. 2 BSEC is less than diesel 3 Carbon monoxide and hydrocarbon emission reduced in case of all blends of Pongamia biodiesel as compare to diesel 4 Carbondioxide and NO_x emission are increased for all blends of Pongamia biodiesel as compare to diesel	[10]
2	**Diesel Engine:** RatedPower: 5.9 kW at 1500 rpm Cylinder bore: 95 mm Stroke length: 110 mm Compression ratio: 17.5:1 Number of cylinder: 1	Pongamia Biodiesel, Diesel	1 B20 has lowest BSFC 2 NO_x emission are higher by (10–25%) for biodiesel 3 CO, HC and smoke emission are reduced in biodiesel 4 Engine performance is similar in case of biodiesel and diesel	[7]
3	**Diesel Engine:** Rated Brake Power: 10/7.4 Rated Speed:1500 Number of cylinder: 1 Cylinder Bore: 102 mm Stroke length: 116 mm Compression ratio: 17.5:1 Cooling system: air cooled	Pongamia Biodiesel, Diesel	1 BTE of diesel is higher as compared to biodiesel by (3–5%) 2 CO_2 and NO_x emission are lower in case of diesel 3 CO and unburnt hydrocarbon emission are lower in case of Pongamia biodiesel	[38]
4	**CI Engine:** Number of cylinder: 3 Rated Speed:2200 rpm Rated Power:44.1 kW	Pongamia Biodiesel (B20, B40, B60, B80, B100), Diesel	1 BSEC is higher in case of pongamia biodiesel 2 CO, HC, Particulate emission and smoke emission are lower in case of Pongmia biodiesel 3 NO_x emission are higher in case of Pongamia Biodiesel 4 Increase of biodiesel proportion from B20 to B100 tends to decrease the smoke level	[36]
5	**CI Engine:** Number of cylinder: 1 Bore:87.5 mm Stroke: 110 mm Compression ratio: 17.5:1 Rated output: 5.2 kW Engine modification: Engine with fly ash coating	Pongamia Biodiesel, Diesel	1 BTE is higher by 4.9% in case of coated engine as compared to uncoated engine by using Pongamia biodiesel 2 BSFC is reduced by 3.2% in case of coated engine 3 HC emission is lower by 11.2% in coated engine 4 Smoke density is reduced by 33.8% in case of coated engine 5 Increase in NO_x emission by 28.6% in case of coated engine	[22]
6	**CI Engine:** Water cooled Rated output: 7.5 kW Compression ratio:16:1	Pongamia biodiesel (B20, B40, B60, B80, B100), Diesel	1 Reduction in CO emission by 73–94% in case of Pongamia biodiesel 2 Smoke emission is reduced by 20–80% 3 NO_x emission is reduced by 26% 4 For B20 and B40 BSFC is reduced by 0.8–7.4% 5 For B60 and B100 BSFC is increased by 11–48% 6 B20 and B40 have higher BTE than diesel 7 B60 and B100 have lower BTE than diesel	[17]
7	**CI engine:** Number of cylinder: 1 Bore:87.5 mm Stroke: 110 mm Compression ratio: 17.5:1 RatedPower: 5.2 kW at 1500 rpm **Engine modification:** 1 Hemispherical combustion chamber 2 Toroidal combustion chamber 3 Shallow depth combustion chamber	Pongamia biodiesel, diesel	1 BSFC of Pongamia biodiesel is higher than diesel. 2 According to combustion chamber design BSFC is in order of: SCC > HCC > TCC 3 BTE of Pongamia biodiesel is less than diesel 4 unburnt Carbon emissions are less for Pongamia biodiesel	[23]
8	**DI Engine:** Rated power: 3.67 kW at 1500 rpm Compression ratio: 17.5:1 Bore:87.5 mm Stroke: 110 mm Water cooled	Pongamia Biodiesel (B20, B40, B60, B80, B100), ,Diesel	1 Thermal efficiency of biodiesel is higher than diesel 2 BSEC is less for Pongamia and its blends 3 CO and HC emission are lower in case of Pongamia biodiesel 4 Smoke emission are higher in case of Pongamia biodiesel	[11]
9	**CI Engine:** Number of cylinder: 1	Pongamia Biodiesel, Diesel	1 BSFC is higher for Pongamia biodiesel 2 20.7% lower HC emission in TRCC compared to HCC 3 44.5% lower CO emission in TRCC compared to HCC	[27]

Table 8 (*continued*)

S. no	Engine specification	Fuel	Results	References
	Bore: 87.5 mmStroke:110 mm Compression ratio: 17.5:1 RatedPower: 5.2 kW at 1500 rpm **Engine modification:** 1 Hemispherical combustion chamber (HCC) 2 Toroidal combustion chamber (TRCC) 3 Shallow depth combustion chamber (SDCC)		4 9.2% of higher NO_x emission in case of TRCC as compared to HCC	

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